MAS350: Assignment 1

Solutions and discussion are written in blue. A sample mark scheme, with a total of 30 marks, is given in red, with each mark placed after the statement/deduction for which the mark would be given. As usual, mathematically correct solutions that follow a different method would be marked analogously.

1. Recall that the Borel σ-field $\mathcal{B}(\mathbb{R})$ is the smallest σ-field on $\mathbb{R}$ containing all open intervals (a, b) with $-\infty < a < b < \infty$. Define

$$A = \bigcup_{n=1}^{N} [a_n, b_n]$$

where $a_1 \leq b_1 < a_2 \leq b_2 < a_3 \leq b_3 < \ldots$ are real numbers.

(a) Prove, starting from the definition given above, that $A \in \mathcal{B}(\mathbb{R})$.

(b) Write down a formula for the Lebesgue measure of A, in terms of the a_i and b_i. Is your formula valid if $N = \infty$?

(c) Consider the following claims.

(i) The Borel σ-field is an infinite set.

(ii) The Borel σ-field contains an infinite number of infinite sets.

(iii) All countable sets are Borel sets with zero Lebesgue measure.

(iv) All Borel sets with positive Lebesgue measure contain at least one open interval.

(v) The Cantor set is a Borel set.

(vi) The Cantor set has Lebesgue measure zero.

In each case (i)-(vi), state whether you believe the claim to be true or false. For claims that you believe are true, give a proof. For claims that you believe are false, give a counterexample. Use parts (a) and (b) to support your arguments.

Solution.

(a) For $b \in \mathbb{R}$, since $(b, n) \in \mathcal{B}(\mathbb{R})$ for all $n > b$, also $\cup_n (b, n) = (b, \infty) \in \mathcal{B}(\mathbb{R})$. [1] Similarly $(-\infty, a) = \cup_n (-n, a) \in \mathcal{B}(\mathbb{R})$ for all a.

Hence, $[a, b] = \mathbb{R} \setminus ((-\infty, a) \cup (b, \infty) \in \mathcal{B}(\mathbb{R})$. [1]

Hence also $A = \cup_{i=1}^{N} [a_i, b_i] \in \mathcal{B}(\mathbb{R})$. [1]

Pitfall: Note that here we are using a particular definition of the Borel sets, which doesn't immediately tell us that half-open intervals such as (a, ∞) are Borel. We can deduce it easily, however. There are many different equivalent definitions.

(b) We have

$$\lambda(A) = \sum_{n=1}^{N} (b_n - a_n).$$

[1] By countable additivity of disjoint sets (from the definition of a measure) this formula is valid when $N = \infty$. [1]

(c) (i) True. For example, $\mathcal{B}(\mathbb{R})$ contains each of the sets $(x, x+1)$, for $x \in \mathbb{R}$, and there are infinitely many of these. [1]

(ii) True. We can use the same example as in (i), because each of the sets $(x, x+1)$ is infinite. [1] *Pitfall:* Make sure you keep track of the difference between a set and a set of sets.

(iii) True. [1] If a set A is countable, the we may write it in the form $A = \cup_{n=1}^{\infty}[a_n, a_n]$. By part (a) this means A is a countable union of Borel sets, and hence is itself Borel. Our formula from part (b) shows that A has Lebesgue measure zero. [1]

(iv) False. [1] Recall that $\mathbb{Q}$ is countable, and hence also a Borel set by the previous part. Hence the irrational numbers $\mathbb{R} \setminus \mathbb{Q}$ are a Borel set. Since $\lambda(\mathbb{Q}) = 0$ we have $\lambda(\mathbb{R} \setminus \mathbb{Q}) = \infty$, but the irrational numbers do not contain any open intervals. [1]

(v) True. Recall the iterative 'middle third' construction of the Cantor set as $C = \cap_n C_n$ (see lecture notes), where $C_1 = [0, 1]$ and C_{n+1} is constructed from C_n by removing the middle third of each closed interval. [1] Thus C_n is the disjoint union of 2^n closed intervals, and we can write it in the form $\bigcup_{n=1}^{N}[a_n, b_n]$. Thus C_n is Borel by part (a), and since σ-fields are closed under countable intersections, we have $C \in \mathcal{B}(\mathbb{R})$ too. [1]

(vi) True. In the iterative 'middle third' construction of the Cantor set as $C = \cap_n C_n$, the n^{th} stage C_n is a union of 2^n disjoint closed intervals each with length 3^{-n}. Using part (b), the Lebesgue measure of C_n is therefore $(\frac{2}{3})^n$. [1] Since the first stage $C_1 = [0, 1]$ has finite measure, in fact $\lambda(C_1) = 1$, this means $\lambda(C) = \lim_n \lambda(C_n) = \lim_n (\frac{1}{3})^n = 0$. [1]

Pitfall: Make sure to use (a) and (b) where they are helpful (as the question asks). In fact, you hardly need to use anything else to solve part (c).

2. Let $\mathcal{B}(\mathbb{R})$ denote the Borel σ-field on $\mathbb{R}$. This question concerns examples of decreasing sequences of Borel sets (B_n) and measures m on $\mathcal{B}(\mathbb{R})$ such that

$$m\left(\bigcap_{n=1}^{\infty} B_n\right) \neq \lim_{N \to \infty} m\left(\bigcap_{n=1}^{N} B_n\right).$$

(a) Let λ denote Lebesgue measure on $\mathbb{R}$. Taking $m = \lambda$, show that $B_n = (-\infty, -n]$ is an example of this type.

(b) Find a second example, with the additional property that $\cap_{n=1}^{\infty} B_n$ is non-empty.

(c) Find a third example, with the additional property that B_1 is countable.

Solution.

(a) We have $\lambda(B_n) = \sum_{j=n}^{\infty} \lambda((-j-1, -j]) = \infty$ and thus $\lim_n \lambda(B_n) = \infty$, [1] but $\cap_n(-\infty, -n] = \emptyset$ which has measure zero. [1]

(b) Take e.g. $B_n = (-\infty, -n] \cup [0, 1]$. Then $\lambda(B_n) = \infty$ as before, but now $\cap_n B_n = [0, 1]$ which is non-empty with Lebesgue measure 1. [2]

(c) Take m to be counting measure on $\mathbb{N}$ (the σ-field can be $\mathcal{P}(\mathbb{N})$ here) and let $B_n = \{n, n+1, \ldots, \infty\}$. and then $m(B_n) = \infty$ but $m(\cap_n B_n) = m(\emptyset) = 0$. [2]

Pitfall: Remember the conditions of the theorem! In general, $m(\cap_n B_n) = \lim_n m(B_n)$ for decreasing B_n *only* if $m(B_1)$ is finite. Once you remember this, you know to start by trying (any) example where $m(B_1)$ is infinite, and from there you don't have far to go.

3. In each of the following cases, show that the given function is measurable, from $\mathbb{R} \to \mathbb{R}$ with the Borel σ-field. State clearly any results from lectures that you make use of.

   (a) $f(x) = \cos x$

   (b) $g(x) = \begin{cases} 0 & \text{for } x < 0 \\ x+1 & \text{for } x \geq 0. \end{cases}$

   (c) $h(x) = \sum\limits_{n=1}^{\infty} \frac{(-1)^n x^n \cos(x)}{n!}$

   (d) $i(x) = \lfloor x \rfloor$ (i.e. x rounded down to the nearest integer)

Solution.

(a) From lectures, every continuous function from $\mathbb{R}$ to $\mathbb{R}$ is measurable. [1] Since cos is continuous, it is measurable. [1]

(b) Let $g_1(x) = \mathbb{1}_{[0,\infty)}(x)$ be the indicator function of $[0,\infty)$, which is measurable because it is the indicator function of a measurable set. [1] Let

$$g_2(x) = \begin{cases} x & \text{if } x > 0 \\ 0 & \text{if } x \leq 0 \end{cases}$$

which is measurable because it is continuous. Then $g(x) = g_1(x) + g_2(x)$ is measurable, because the sum of measurable functions is measurable. [1]

(c) First note that $|\frac{(-1)^n x^n \cos(x)}{n!}| \leq |\frac{x^n}{n!}|$ and since the power series $e^x = \sum_{n=1}^{\infty} \frac{x^n}{n!}$ converges for all x, so does the series for $h(x)$. [1]

We have that $\cos(x)$ is measurable from (a), $f(x) = x^n$ is continuous and hence measurable, thus $x \mapsto \frac{(-1)^n x^n \cos(x)}{n!}$ is measurable, because sums and products of measurable functions are measurable. [1]

Since limits of measurable functions (when they exist) are measurable [1] we have that $h(x)$ is measurable.

(d) $i(x)$ is an increasing function of x, [1] and increasing functions are measurable. [1]

Alternatively: if $x \in [n, n+1)$ then

$$f^{-1}((x,\infty)) = \{y \in \mathbb{R} \,:\, \lfloor y \rfloor > x\} = \{y \in \mathbb{R} \,:\, \lfloor y \rfloor \geq n+1\} = [n+1, \infty)$$

is a Borel set. Here we use that f is measurable if and only if $f^{-1}((c,\infty)) \in \mathcal{B}(\mathbb{R})$ for all $c \in \mathbb{R}$.

Pitfall: Make sure to specify which results (from lectures) you use to make your deductions.